Mass Transport by Second Mode Internal Solitary Waves

Alan Brandt, PI
Johns Hopkins Univ. Applied Physics Laboratory
Laurel, MD 20723
phone: (240) 228-5915 fax: (240) 225-6908 email: alan.brandt@jhuapl.edu

Omar M. Knio, co-PI
Dept. of Mechanical Engineering & Material Science, Duke University
Durham, NC 27708
phone: (919) 660-5344 fax: (919) 660-8963 email: omar.knio@duke.edu

Award Number: N00014-12-01-0385
http://jhuapl.edu

LONG-TERM GOALS

The overall scientific objective of the proposed effort is to improve our understanding of the propagation and mass transport of internal solitary waves (ISW), particularly mode-2 ISW, and their significance for coastal ocean processes. In recent years numerous observations of mode-2 ISW have been reported so that it appears that such waveforms may be more prevalent than previously thought. Large amplitude mode-2 solitary waves have unique properties, in particular they encompass regions of internal recirculation that enable mass transport over large distances. Transport of mass along a pycnocline can affect upper ocean mixing and distribution of biological and chemical constituents. Moreover, coherent ISW packets can have significant effects on the propagation and scattering of acoustic signals.

OBJECTIVES

The objectives of the current effort are to: (1) improve our fundamental understanding of mode-2 ISW mass transport including the effects of ambient shear; (2) characterize the three-dimensional mass transport from localized sources; and, (3) use the results to aid in the interpretation of ocean observations and ascertain the implications for ocean mixing and bio-chemical transport.

APPROACH

Increased understanding of mass transport will be achieved by a combined series of numerical simulations and scaled laboratory experiments focused on determining the extent and persistence of ISW mass transport.

The numerical simulations of mode-2 ISW (O.M. Knio, Duke Univ.) will be based on the Boussinesq model developed by Terez & Knio (1998) and recently extended by Salloum et al. (2012). The model integrates the mass and momentum conservation equations and simulates the motion of Lagrangian particles, used to characterize and quantify mass transport. Also modeled is the evolution of a passive scalar and of a Lagrangian particle field, both used to analyze mixing and to compare predictions to experimental measurements. The extended model will:

Report Documentation Page					*Form Approved* *OMB No. 0704-0188*
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE **30 SEP 2013**		2. REPORT TYPE			3. DATES COVERED **00-00-2013 to 00-00-2013**
4. TITLE AND SUBTITLE **Mass Transport by Second Mode Internal Solitary Waves**					5a. CONTRACT NUMBER
					5b. GRANT NUMBER
					5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)					5d. PROJECT NUMBER
					5e. TASK NUMBER
					5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Johns Hopkins University,Applied Physics Laboratory,Laurel,MD,20723**					8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)					10. SPONSOR/MONITOR'S ACRONYM(S)
					11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

1. Account for the presence of current shear,
2. Extend the model so as to account for the 3D evolution of a mode-2 ISW,
3. Incorporate higher-order discretization that would enable efficient computations of ISW at higher Reynolds numbers in order to more accurately simulate ocean conditions.

The laboratory experiments (A. Brandt, JHU/APL) will extend earlier (Brandt, 2007) and more recent studies on ISW mass transport (Brandt et al., 2011) in the existing two-layer interfacial tank. Basic wavefield properties (amplitude, wavelength, etc.) are measured by imaging the evolution of the dye initially placed in the mixed generation region. Mass transport is determined by imaging the area of the dye included in the ISW bulge. Laser sheet imaging of fluorescent dye will be employed to ascertain the dynamics of the internal recirculation patterns in the large-amplitude ISW. PIV will also be employed to determine local velocities in the vicinity and within the ISW bulges. These studies will:

1. Investigate the efficiency of various mechanisms for ISW generation and mass transport to simulate the candidate ocean forcing conditions.
2. The effects of ambient shear flow on ISW generation/propagation process will be studied in the JHU/APL interfacial shear tunnel.
3. ISW mass transport and spreading in 3D, simulating the evolution of ISW in the coastal ocean, will be investigated in 3D (square) stratified tank, to provide an understanding of the extent of mass transport and a comparison to the 2D case.

WORK COMPLETED

The earlier numerical study on mode-2 ISW mass transport has been completed and published: Salloum, Knio & Brandt (2012). Preliminary experimental results have been presented at the APS DFD meeting: Brandt, et al. (2011). A manuscript descrobomg the experimental results has been submitted for publication (Brandt & Shipley, 2013), and a further manuscript on the numerical simulatins is in preparation (Rizzi & Knio, 2013).

A series of laboratory experiments using different mechanisms for ISW generation and mass transport (to simulate the candidate ocean forcing conditions) has been completed and analysis is in progress. The generation mechanisms investigated include:

- Mixed region release (“dam break”) – simulating front/intrusion ISW generation
- Ocsillating mixer – simulating internal wave generated mixing
- Rotating paddle mixer – simulating internal wave instabilities
- Forced wedge displacement – simulating flow over a seamount.

In addition, experiments are in progress to measure the recirculation patterns within the mode-2 ISW bulge using particle imaging velocimetry (PIV).

On the computational side, our efforts have focused on:

- Extension of our previous model (Salloum et al., 2012) in order to account for the impact of shear on ISW, and implementation of the extended solver to characterize the impact of Richardson number on the evolution of mode-2 ISW and their mass transport properties; and,
- Formulation and development of a new, high-order primitive-variable Boussinesq solver that will be primary tool for analyze the behavior of ISW in three dimensional settings.

RESULTS

The laboratory studies performed are the first quantitative measurements of the mass transport by mode-2 internal solitary waves propagating on a thin pycnocline. The general nature of the evolving flow can be seen in the photo in fig. 1. Representative images of the leading mode-2 ISW for small and large amplitude conditions are shown in fig. 2.

While all the ISW generated were large-amplitude, i.e. had internal recirculating regions and transported mass, they generally were of three types: $a/h < 2$, (a is the amplitude of the ISW and h is the characteristic pycnocline thickness) small-amplitude ISW with a smooth front face; $2 < a/h < 4$, large-amplitude ISW with an open mouth, "PacMan" opening where external fluid was entrained into the bulge; and, $a/h > 4$, very large-amplitude ISW again with smooth front face likely due to strong internal recirculation; the latter two are illustrated in fig. 2. In all cases a dye trail behind the leading wave was evident, composed of fluid from the dye release intrusion and detrained fluid exiting the downstream end of the bulge. This fluid was in part entrained into the 2nd (following) ISW. In the very large-amplitude waves, e.g. fig. 2(b), local mixing instabilities are apparent at the ISW bulge aft end.

The recirculation within the large amplitude mode-2 ISW results in the transport of mass, Φ. This is measured by the cross-sectional area of the ISW bulge. At the highest level of ISW forcing over 40% of the initially mixed fluid was transported within the leading ISW. Fig. 3 shows Φ scaled by h^2 vs. a/h, for all experimental runs. With this scaling the data for all forcing conditions collapse onto two curves separated at $a/h \cong 4$. The larger values of a/h define a new regime where the ISW wavelength and extent of mass transported increased with amplitude at a rate greater than the smaller amplitude ISW.

The laboratory experiments using different mechanisms for ISW generation and mass transport have shown qualitatively significant differences in the amplitudes of the ISW and thus the potential for mass transport. Detaled analysis of these data is in progress.

The numerical simulation effort included both code development and investigation using the code. This vorticity-based model was employed to analyze the dynamics of internal solitary waves generated by the collapse of a mixed region, and to investigate the resulting transport of mass away from the generation zone. The significant effect of increasing Re is illustrated in Fig. 4, where two different initial forcings, H, are shown as the top/bottom of half of the symmetric mode-2 ISW in each of the panels.

The computations were used to examine the impact of background shear on the mass transport characteristics of the solitary waves. In particular, our study indicates that mass transport by the waves is limited by internal mixing associated with intrinsic flow instabilities. In the absence of background shear, the dominant mechanism appears to be associated with Kelvin-Hemholtz instabilities, whereas in the presence of shear the dominant mechanism is associated with amplification of Holmboe modes.

Consistent with these observations, our analysis also indicates that when the thickness of the shear profile is large, the mass transport rate increases with Richardson number.

The numerical solver has also been extended to three-dimensions, and will be applied to investigate the role of 3D instability and turbulence on the dynamics and mass transport of ISW and of the impact of background shear.

IMPACT/APPLICATIONS

Transport of mass along a pycnocline can affect upper ocean mixing and distribution of biological and chemical constituents. Coherent ISW packets can also have significant effects on the propagation and scattering of acoustic signals. The present fundamental investigation of mode-2 ISW can aid in interpretation of ocean observations of ISW and their mass transport effects.

TRANSITIONS

The results of this effort will be transitioned to Navy programs concerned with ocean wave dynamics and vehicle signatures.

RELATED PROJECTS

ONR Code 331 study of Body Generated Internal Waves. This study complements the present effort by relating basic oceanographic processes to those involving wave generation by Navy assets.

REFERENCES

Brandt, A. 2007 "Evolution of Mode-2 Solitary Internal Waves in a Stratified Shear Flow." Fifth International Symposium on Environmental Hydraulics (ISEH V), Tempe, Arizona, 4-7 December 2007, 6 pp.

Brandt, A. & Shipley, K.R, Salloum, M. & Knio, O.M. 2011 "Mass Transport by Large Amplitude Internal Solitary Waves," 64th Annual Meeting of the Am. Phys. Society Division of Fluid Dynamics (DFD), 20-22 November 2011, Baltimore, MD.

Terez, D.E., Knio, O.M., "Numerical simulations of large-amplitude internal solitary waves", *J. Fluid Mech. 362,*53-82 (1998).

PUBLICATIONS

Brandt, A., K.R. Shipley, 2013 "Laboratory Experiments on Mass Transport by Large Amplitude Mode-2 Internal Solitary Waves," *Phys. Fluid.* [submitted, referred]

Rizzi, F., G. Li, O.M. Knio, 2013 "Numerical Simulations of Deep Density Currents," *J. Fluid Mech.* [in preparation]

Salloum, M., Knio, O.M., Brandt, A., "Numerical Simulation of Mass Transport in Internal Solitary Waves," Phys. Fluids, 24, 016602 (2012); doi: 10.1063/1.3676771. [published, refereed]

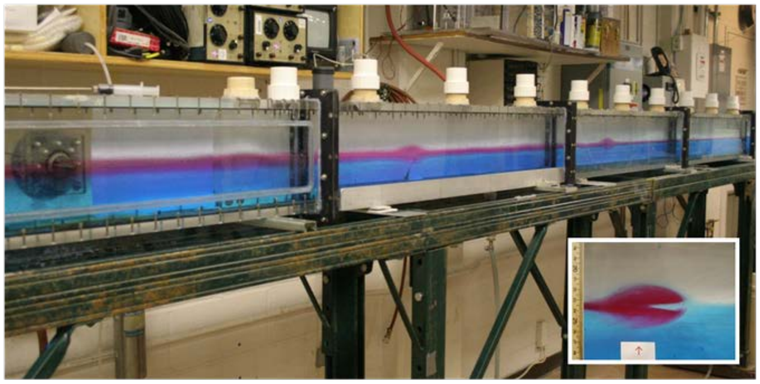

Figure 1. Stratified shear tunnel showing mode-2 ISW propagating on the thin interface (red). Upper clear layer is fresh water; bottom, blue layer is high density salt. Inset shows enlargement of large amplitude ISW entraining fluid at the leading edge.

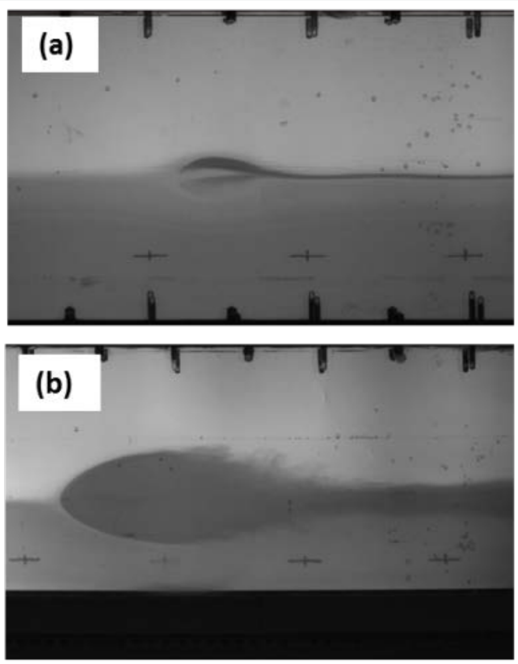

Figure 2. Representative ISW bulge waves,:
(a) intermediate large-amplitude, $a_b/h = 1.96$;
(b) very large-amplitude, $a_b/h = 5.92$.

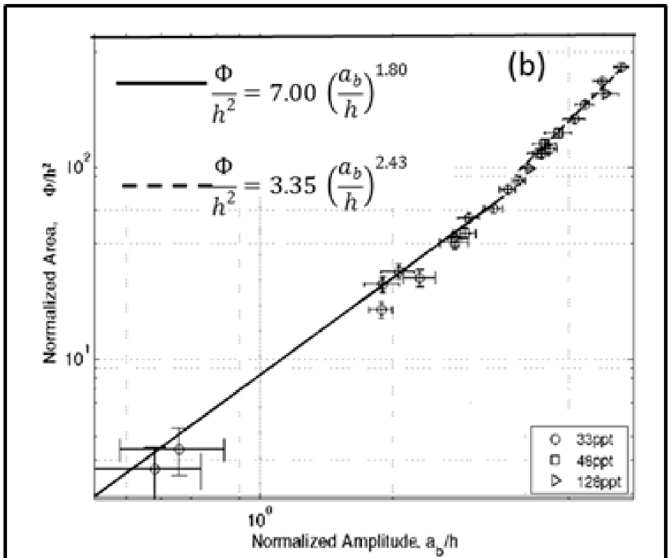

Figure 3. Mass transport by mode-2 ISW

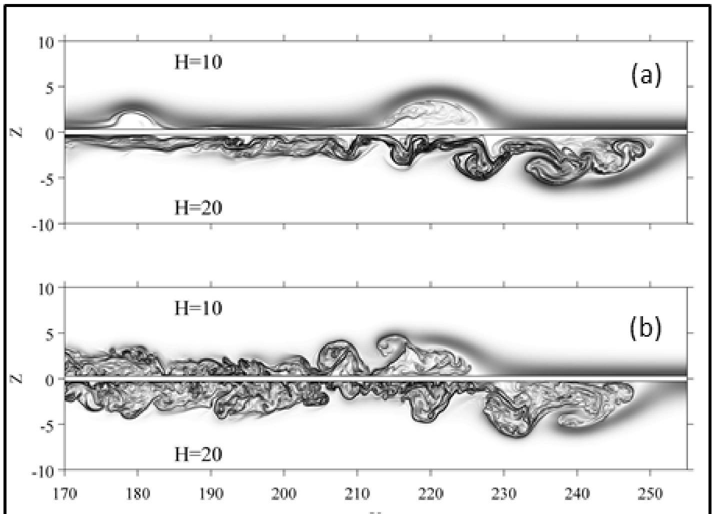

Figure 4. Reynolds number effects on mode-2 ISW.
(a) Re = 100, (b) Re = 1500.